r_{inv} Parameters

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1 Definitions

The dark sector has an $SU(N_c^{\text{dark}})$ force with N_f^{dark} dark quarks χ_i, where i is the flavor index. The scale of the dark force is Λ_{dark}. We define $r_{\text{inv}} = \langle N_{\text{stable}}/(N_{\text{stable}} + N_{\text{unstable}})\rangle$, where N_{stable} and N_{unstable} refer to the multiplicities of stable and unstable dark hadrons in an event, respectively.

All models discussed below are built on the initial hidden valley model from Ref. [1].

2 Cohen model

Ref. [2] defines $N_c^{\text{dark}} = 2$ and introduces a Z$'$ mediator that couples to both SM quarks and dark quarks, with flavor-diagonal couplings g_{q} and g_χ, respectively.

Accidental symmetries, using i and j to represent dark quark flavor indices:

- Dark isospin number: $U(1)_{i-j}$
- Dark baryon number: $U(1)_{i+j}$

These symmetries imply the following spectrum:

Type	Flavor	States	Stable?
Meson	Diagonal	$\chi_i^\dagger \chi_i$	No
Meson	Off-diagonal	$\chi_i^\dagger \chi_j$, h.c.	Yes (dark isospin)
Baryon	Diagonal	$\chi_i^\dagger \chi_j^\dagger$, h.c.	Yes (dark baryon number)

Baryon production is suppressed by $1/(N_c^{\text{dark}})^2$, so meson production dominates. The different dark meson states are taken to be mass degenerate.

The production of stable mesons is suppressed when $m_{\chi_j}^2 - m_{\chi_i}^2 > \Lambda_{\text{dark}}^2$. This suppression occurs in the Lund string model fragmentation factor:

$$T = \exp\left(-\frac{4\pi|m_{\chi_j}^2 - m_{\chi_i}^2|}{\Lambda_{\text{dark}}^2}\right). \tag{1}$$

The production of stable mesons is proportional to $N_f^{\text{dark}}(N_f^{\text{dark}}-1)$, while the production of unstable mesons is proportional to N_f^{dark}. Therefore, the proportion of stable mesons increases with N_f^{dark}.

3 Schwaller model

Ref. [3] defines $N_c^{\text{dark}} = 3$ and introduces a bifundamental scalar mediator Φ that has Yukawa couplings between right-handed SM quarks and dark quarks. (This type of mediator is also explored in Ref. [4].) To avoid flavor-changing processes, flavor symmetries or other SM-like flavor structures are usually assumed.

This model assumes that all dark pions π_{dark} decay to SM, but potentially with some finite lifetime τ_{dark}. More massive dark hadron states are assumed to decay promptly to π_{dark}.

It is also noted that N_f^{dark} cannot be increased arbitrarily; for $N_f^{\text{dark}} \gtrsim 4N_c^{\text{dark}}$, the model stops behaving like QCD (because of an infrared fixed point).

r_{inv} is small in these models because of the suppression of baryon production. However, it is noted that if $m_{\pi_{\text{dark}}}$ is similar to the mass scale of heavier dark hadrons (rather than parametrically smaller), baryon production would no longer be suppressed and heavier dark hadrons would no longer be able to decay to dark pions.

Ref. [5] considers a more complex case where different dark hadrons have different lifetimes, depending on their dark quark flavor content. It is noted that an unbroken $U(N_f^{\text{dark}} - 3)$ symmetry arises for $N_f^{\text{dark}} > 3$, which can make some dark pion states stable.

4 Aachen model

Ref. [6] (see also Ref. [7]) explores a model similar to the one described in Section 2. It sets $N_c^{\text{dark}} = 3$ and $N_f^{\text{dark}} = 2$. Dark baryons are assumed to be sufficiently heavy that they are irrelevant.

It further introduces a "dark G-parity" such that all dark pions are stable. It notes that diagonal dark pions would not be stable if $N_f^{\text{dark}} = 3$ were chosen instead. The (collider-scale) stability of the off-diagonal dark rhos ρ_{dark} relies on the assumption $m_{\rho_{\text{dark}}} < 2m_{\pi_{\text{dark}}}$, which restricts ρ_{dark} to decay through a suppressed three-body anomaly decay ($\pi_{\text{dark}}\text{q}\overline{\text{q}}$). Diagonal ρ_{dark} decay to SM quarks via mixing with the Z' mediator.

Assuming the multiplicity of ρ_{dark} is a factor 3 higher than the multiplicity of π_{dark} (corresponding to the PYTHIA parameter `probVector`) and the multiplicity of off-diagonal dark mesons is twice that of diagonal mesons, r_{inv} is expected to be 0.75.

5 Snowmass model

Ref. [8] considers confining theories with $N_f^{\text{dark}} < 3N_c^{\text{dark}}$. The dark hadron content of these theories includes: $(N_f^{\text{dark}})^2 - 1$ mass-degenerate dark pions and dark rhos, along with the corresponding flavor singlets η'_{dark} and ω_{dark}. The former singlet is nearly degenerate with π_{dark} for $N_f^{\text{dark}} \ll N_c^{\text{dark}}$ but much heavier for $N_f^{\text{dark}} \sim N_c^{\text{dark}}$, while the other states follow a hierarchy $m_{\pi_{\text{dark}}} < m_{\rho_{\text{dark}}} \lesssim m_{\omega_{\text{dark}}}$. Relationships between m_χ, $m_{\pi_{\text{dark}}}$, and $m_{\rho_{\text{dark}}}$ are obtained from lattice theory. (If $N_c^{\text{dark}} = 2$, the dark baryons are degenerate with the dark pions, as in Section 2.)

This model notes that `probVector` $= 0.75$ is true when π_{dark} and ρ_{dark} are mass degenerate, while `probVector` $=$ 0.5 for SM QCD. Probabilities for producing η'_{dark} and dark baryons may also need to be specified.

The decays of the dark mesons depend on the dark quark charge matrix $\mathbf{Q}$, which may take different values, and on the mass relationships between the different bound states. Two regimes are explored:

- Regime 1: $2m_{\pi_{\text{dark}}} < m_{\rho_{\text{dark}}}$; `probVector` $= 0.5$; $N_c^{\text{dark}} = 3$; $N_f^{\text{dark}} = 3$; the ρ_{dark} decay to $\pi_{\text{dark}}\pi_{\text{dark}}$, while the π_{dark} may decay via mixing with the Z$'$ (dark quark and mediator masses from dark Higgs sector). This regime has $k = 0, 1,$ or 2 diagonal dark pions and all off-diagonal pions as stable, leading to $r_{\text{inv}} = (6 + k)/9$.
- Regime 2: $2m_{\pi_{\text{dark}}} > m_{\rho_{\text{dark}}}$; `probVector` $= 0.58$; $N_c^{\text{dark}} = 3$; $N_f^{\text{dark}} = 4$; the ρ_{dark} decay through an anomaly (as in Section 4, while the π_{dark} are stable (no mixing with Z$'$; dark quark masses and mediator masses from separate sources).

r_{inv} is difficult to calculate analytically in Regime 2 because of the partially-invisible anomaly decay. I propose integrating the vertex to get the average momentum fraction of the dark pion in this decay and multiplying the dark rho multiplicity by this value to estimate r_{inv}. This procedure needs to be validated (by comparison to PYTHIA output) and may need to become more complex to handle boosts. The lower bound is $r_{\text{inv}} \geq 1 -$ `probVector` $= 0.42$.

In Regime 2, the anomaly decay can be eliminated by certain choices of $\mathbf{Q}$, leading to stability on the detector scale for ρ_{dark} in those cases.

6 Other considerations

Dark hadron lifetimes

Dark hadron decay patterns (flavor)

Mediator and/or portal type(s) (production vs. decay)

7 Summary of parameters

The parameters that may influence r_{inv} include:

- N_c^{dark}: baryon suppression
- N_f^{dark}: diagonal vs. off-diagonal meson frequency, other symmetries
- dark quark mass splitting (relationship of m_{χ_i}, m_{χ_j}, Λ_{dark}): off-diagonal meson suppression
- dark hadron mass spectrum ($m_{\pi_{\text{dark}}}$, $m_{\rho_{\text{dark}}}$, etc.): baryon suppression, heavier state decays (two-body vs. three-body), relative abundance of pseudoscalar vs. vector mesons
- dark G-parity (if any): stability of dark pions
- $\mathbf{Q}$ (mediator charges for dark quarks): decay availability
- Mass mechanisms (dark Higgs sector or something else): determines Z$'$ mixing

References

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